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Kicked Neutron Stars and Microlensing

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ABSTRACT

Due to the large kick velocities with which neutron stars are born in supernovae explosions, their spatial distribution is more extended than that of their progenitor stars. The large scale height of the neutron stars above the disk plane makes them potential candidates for microlensing of stars in the Large Magellanic Cloud. Adopting for the distribution of kicks the measured velocities of young pulsars, we obtain a microlensing optical depth of $\tau \sim 2N_{10} \times 10^{-8}$ (where N_{10} is the total number of neutron stars born in the disk in units of 10^{10}). The event duration distribution has the interesting property of being peaked at $T \sim 60-80$ d, but for the rates to be relevant for the present microlensing searches would require $N_{10} \gtrsim 1$, a value larger than the usually adopted ones ($N_{10} \sim 0.1-0.2$).

The ongoing searches of baryonic dark matter in the Galaxy by means of microlensing of stars in the Large Magellanic Cloud (LMC) have produced very surprising results recently. Indeed, the first five events obtained by the EROS (Aubourg *et al.* 1993) and MACHO (Alcock *et al.* 1995) collaborations, with durations $T \sim 10-29$ d, suggested the presence of compact objects with masses $\sim 0.1M_\odot$, i.e. near the brown dwarf range. However, the new analysis of the first two years of MACHO observations (Alcock *et al.* 1996) has now returned events with longer durations (besides eliminating their two shortest duration events). These new results are indicative of larger lens masses, in the range $0.1-1M_\odot$, being responsible for the events. In addition, the large event rates observed require a considerable amount of compact objects to be present in the Galaxy.

A first difficulty associated with the new range of inferred masses is that the lensing population can no longer be completely ascribed to the unseen brown dwarf counterpart of one of the Galactic stellar components, such as the thick disk (Gould, Miralda–Escudé and Bahcall 1994) or the spheroid (Giudice, Mollerach and Roulet 1994). Although a population of white dwarf remnants in these components could help to fit the observed

MACHO event durations, it would require an initial mass function quite contrived in order to have $\gtrsim 90\%$ of the mass of these components ending up in white dwarfs, and even in this case the resulting rates would still fall short with respect to the observed ones. On the other hand, the proposed interpretation of the lenses being an old white dwarf population in the dark halo makes the problem of the absence of any luminous stellar counterpart more severe than for the previous scenarios.

In this letter, we want to study the relevance for the microlensing searches of the other natural candidate for dark lensing objects in the Galaxy: the neutron stars (NS). An important point to take into account in the study of the population of neutron stars in the Galaxy is the fact that the violent birth of these objects in supernova (SN) explosions makes them acquire large 'kick' velocities, as evidenced by the observed velocities of young pulsars (fastly rotating magnetized neutron stars). The pulsar velocities have been studied by Lyne and Lorimer (1994), who obtained a fit to the observed distribution of transverse speeds v_t given by

$$f_{2D}(v_t) \propto \frac{t^{0.13}}{1+t^{3.3}}, \tag{1}$$

where $t = v_t/(330 \text{ km/s})$. Under the assumption that the kick distribution is isotropic, the two dimensional distribution is just a convolution of the underlying three dimensional distribution $f_{3D}(v)$,

$$f_{2D}(v_t) = v_t \int_{v_t}^{\infty} dv \frac{f_{3D}(v)}{v\sqrt{v^2 - v_t^2}}. \tag{2}$$

Hence, f_{3D} can be reconstructed by solving an Abel integral equation, to obtain[1]

$$f_{3D}(v) = -\frac{2}{\pi} \int_{v}^{\infty} dv_t \frac{df_{2D}}{dv_t} \frac{v_t}{\sqrt{v_t^2 - v^2}}. \tag{3}$$

The average velocity resulting from this distribution is $\langle v \rangle \sim 390$ km/s. This implies that the NS born from a given Galactic population (e.g. the disk or the bulge) will end up with a completely different, and much more extended, spatial distribution. The physical origin of these kick velocities is still unknown, and proposed mechanisms include the unbinding of a close binary system (Dewey and Cordes 1987, Bailes 1989), an asymmetric explosion (Burrows *et al.* 1995) or the interaction of the emitted neutrinos with the NS magnetic field (Kusenko and Segrè 1996).

The spatial distribution of the NS born from massive disk stars during the whole lifetime of the Galaxy has been considerably studied as a possible Galactic source of gamma

[1]The result obtained here is equivalent to the one of Terasawa and Hattori (1995).

ray bursts (Shklovskii and Mitrofanov 1985, Li and Dermer 1992, Podsiadlowski, Rees and Ruderman 1995). The neutron stars density can be obtained from Monte Carlo simulations of the initial distribution of neutron star locations and kick velocities at birth, and then following their orbits in the Galactic gravitational potential up to the present (Paczyński 1990, Hartmann, Epstein and Woosley 1990, Terasawa and Hattori 1995). In particular, in order to fit the isotropy of the BATSE observations (Meegan *et al.* 1992), the gamma ray bursts in these Galactic scenarios must be produced by the very distant tail of the spatial NS distribution, i.e. at Galactocentric distances $r \gtrsim 100$ kpc. As we will show, a large fraction of the neutron stars born in the disk ($\sim 30\%$) contributes to the density at radii 8 kpc $< r <$ 40 kpc (having a considerable height above the disk plane). Hence, independently of their possible relevance to account for the gamma ray bursts, the NS can effectively act as lensing objects in the microlensing searches in the direction of the LMC.

To compute the NS distribution we follow closely the work of Paczyński (1990), but with the currently accepted velocity distribution, eqs. (1,3). We take for the radial distribution of the initial birth positions

$$dP(R) \propto \exp(-R/h_R) R dR, \tag{4}$$

taking for the disk scale length $h_R = 3.5$ kpc. For simplicity, we take z$=0$ for the initial NS vertical positions, since anyhow very massive disk stars form with a small scale height (< 100 pc), so that this assumption is not essential for the microlensing results. With these distributions, we produced 1.6×10^5 initial values of positions and velocities and followed the orbits by integrating the equations of motion (using cylindrical coordinates)

$$\frac{dR}{dt} = v_R, \qquad \frac{dv_R}{dt} = -\frac{\partial\Phi}{\partial R} + \frac{J_z^2}{R^3}, \tag{5}$$

$$\frac{d\mathrm{z}}{dt} = v_z, \qquad \frac{dv_z}{dt} = -\frac{\partial\Phi}{\partial \mathrm{z}} \tag{6}$$

in the Galactic gravitational potential Φ. In addition, we have the equations stating the conservation of the angular momentum and the energy

$$\begin{aligned} J_z &= R v_\phi = \text{const}, \\ E &= v_R^2 + v_z^2 + v_\phi^2 + \Phi(R,\mathrm{z}) = \text{const}. \end{aligned} \tag{7}$$

In particular, we used the energy conservation to check that the final accuracy for this quantity after the numerical integration was better that 10^{-6}.

We model the Galaxy with three dynamical components, a disk, a bulge and a dark halo, with $\Phi = \Phi_d + \Phi_b + \Phi_h$. For the disk and bulge components we used Miyamoto and

Nagai (1975) potentials given by

$$\Phi_i = -\frac{GM_i}{\sqrt{R^2 + \left(a_i^2 + \sqrt{z^2 + c_i^2}\right)^2}}, \qquad (i = d, b). \tag{8}$$

For the halo we took a logarithmic potential (Binney and Tremaine 1987)

$$\Phi_h = \frac{1}{2}v_0^2 \ln\left(R_c^2 + R^2 + \frac{z^2}{q_\phi^2}\right) + \text{const}, \tag{9}$$

allowing in principle for a non–spherical distribution ($q_\phi \neq 1$) in order to explore the effects of a flattened halo. The corresponding mass densities can be obtained from the Poisson equation $\nabla^2\Phi = 4\pi G\rho$. The parameters in eqs. (8) are chosen so as to produce an acceptable rotation curve, and are $M_d = 8.07 \times 10^{10} M_\odot$, $a_d = 3.7$ kpc, $c_d = 0.2$ kpc for the disk and $M_b = 1.12 \times 10^{10} M_\odot$, $a_b = 0$, $c_b = 0.227$ kpc for the bulge, with $v_0 = 200$ km/s and $R_c = 10$ kpc for the halo potential.

The resulting local column density, for a solar Galactocentric distance of 8.5 kpc, is $\Sigma_0(|z| < 1.1 \text{ kpc}) = 79 M_\odot/\text{pc}^2$ (for $q_\phi = 1$), which is consistent with the dynamical estimates from vertical motion of stars (Kuijken and Gilmore 1991), and increases to $\sim 85 M_\odot/\text{pc}^2$ for $q_\phi = 0.8$ (which corresponds to and axis ratio in the density distribution $q_\rho \simeq 0.4$ (Binney and Tremaine 1987)). The rotation curve velocity, $v_c^2 = R\partial\Phi/\partial R|_{z=0}$, is clearly insensitive to q_ϕ.

Regarding the total number of neutron stars produced during the whole Galaxy lifetime, this is a quantity which is not easy to estimate, since it depends crucially on the initial mass function of heavy stars ($m > 8M_\odot$). This is quite uncertain, mainly because of the unknown evolution of the star formation rate from the birth of the Galaxy up to our days. If the present accepted rate of Type II and Ib (core collapse) supernovae of $\sim 0.02 - 0.03$ yr^{-1}, which is consistent with the estimated pulsar birth rate (Lyne, Manchester and Taylor 1985), were to be representative of the average SN rate in the past, one would estimate a total number of neutron stars produced in the disk $N \simeq 3 \times 10^8$. However, the star formation rate was certainly higher at earlier times, mainly due to the larger fraction of gas present in the past and to the possibility of an initial burst of star formation. This can enhance a lot the fraction contributed by the heavy stars to the initial mass function (Larson 1986). For instance, a recent modeling of the SN production in the Galaxy (Timmes, Woosley and Weaver 1995, 1996) concluded that a more reasonable value for the total number of neutron stars is $N_{NS} \simeq 1.9 \times 10^9$, but the uncertainty in this number is undoubtedly large. In view of this, we will not adopt a definite value for N_{NS}, giving the results in terms of $N_{10} = N_{NS}/10^{10}$, hoping that in the future this number will be known

more precisely. Since in the models leading to $N_{10} \gtrsim 0.1$ most of the SN explosions took place in the early life of the Galaxy, we just assumed for the Monte Carlo simulations that the NS were all born 10^{10} years ago. The results are in any case nearly unchanged for a uniform distribution of birth times.

Figure 1 shows the number density contours of the resulting NS distribution. This distribution is more extended than the one obtained by Paczyński (1990) and Hartmann, Epstein and Woosley (1990), due to the smaller velocities adopted at the time by those authors. We have indicated also in the plot the coordinates of the line of sight to the LMC (which position at $(R,\mathrm{z})_{LMC} = (42, -26.5)$ kpc is also labeled), assuming a distance to it of $D_{os} = 50$ kpc. Looking at this curve, it is useful to recall that using the parameter $x \equiv D_{ol}/D_{os}$ to describe the normalized distance along the line of sight to an hypothetical lensing object, at distance D_{ol} from the Sun, one has $x = \mathrm{z}/\mathrm{z}_{LMC}$.

From the resulting NS density we can now compute the microlensing optical depth (for reviews on microlensing see Roulet and Mollerach (1996) and Paczyński (1996))

$$\tau = \int_0^1 dx \frac{d\tau}{dx}, \tag{10}$$

with

$$\frac{d\tau}{dx} = \frac{4\pi G}{c^2} D_{os}^2 x(1-x)\rho(x), \tag{11}$$

where ρ is the mass density of the lenses, for which we just assume a common NS mass of $1.4 M_\odot$. The resulting value is $\tau = 1.9 N_{10} \times 10^{-8}$. Also, defining

$$\langle D_{ol} \rangle = \frac{1}{\tau} \int_0^1 dx \frac{d\tau}{dx} D_{ol}, \tag{12}$$

we find an average distance to the lenses of $\langle D_{ol} \rangle \simeq 8.8$ kpc, which shows that the lenses are indeed quite far away (we recall that $\langle D_{ol} \rangle \simeq 1.1, 3.6$ and 14 kpc for objects in a thin disk, thick disk and dark halo respectively).

Another important quantity to describe the microlensing events is the distribution of event durations. To obtain it one needs the distribution of the velocities with which the lensing objects cross the line of sight to the LMC. To this end, we obtained the velocities of the NS which were near to the line of sight, computed the relative velocities with respect to this line, and then took the projections of these relative velocities orthogonal to the same line. If $\mathbf{v}_o$ and $\mathbf{v}_s$ are the velocities of the Sun and the LMC respectively, the motion of the line of sight (and hence of the so-called microlensing tube) is just $\mathbf{v}_t = (1-x)\mathbf{v}_o + x\mathbf{v}_s$. In a coordinate system where $\hat{\mathbf{x}}$ points toward the Galactic center and $\hat{\mathbf{y}}$ along the direction of increasing longitudes, we adopted, following Griest (1991), $\mathbf{v}_o = (9, 231, 16)$ km/s and

$\mathbf{v}_s = (53, -160, 162)$ km/s. The quantity of interest is

$$v_\perp = |\mathbf{v}_r - (\mathbf{v}_r \cdot \hat{L})\hat{L}|, \tag{13}$$

where $\mathbf{v}_r = \mathbf{v}_l - \mathbf{v}_t$ is the relative velocity, with $\mathbf{v}_l$ being the lens velocity which we obtained with the Monte Carlo. $\hat{L} = (\cos b \cos \ell, \cos b \sin \ell, \sin b)$ is the versor in the direction of the LMC, which has Galactic coordinates $(b, \ell)_{LMC} = (-33^\circ, 281^\circ)$.

The duration of the events is given by $T \equiv R_E/v_\perp$, with the Einstein radius being $R_E = 2\sqrt{GmD_{os}x(1-x)}/c$. The inclusion of the tube velocity is relevant in this scenario, contrary to the case of lenses in a halo, mainly due to the importance of the observer's motion and the 'memory' that the NS have of their progenitor's motion of rotation.

We can compute now the 'theoretical' rate of events (assuming unit efficiency) from

$$\langle\Gamma\rangle_{th} = \int_0^1 dx \frac{d\langle\Gamma\rangle_{th}}{dx}, \tag{14}$$

where

$$\frac{d\langle\Gamma\rangle_{th}}{dx} = \frac{2}{\pi}\frac{d\tau}{dx}\frac{1}{\langle T\rangle(x)}, \tag{15}$$

with $\langle T\rangle(x) = R_E(x)\langle v_\perp^{-1}\rangle(x)$. The resulting value is $\langle\Gamma\rangle_{th} = 0.4N_{10}$ events/(10^7 stars yr). We can equally compute the 'theoretical' average event duration from the relation

$$\langle T\rangle = \frac{2}{\pi}\frac{\tau}{\langle\Gamma\rangle_{th}}, \tag{16}$$

resulting in $\langle T\rangle \simeq 115$ d.

The event duration distribution can be obtained from the underlying distribution of velocities $v_\perp$ as a function of x. We have computed it by dividing the event durations in bins of $\Delta T = 10$ d, i.e. considering the intervals $[T_i, T_i + \Delta T]$ with $T_i = \Delta T \times i$, and obtaining the fraction $f_i(x)$ of the events with durations in the specified intervals to estimate the differential distribution $df(x,T)/dT$ of this fraction. The differential rate can then be computed using

$$\frac{d\Gamma}{dT}(T) = \frac{2}{\pi}\int_0^1 dx \frac{d\tau}{dx}\frac{1}{T}\frac{df(x,T)}{dT}. \tag{17}$$

The resulting distribution is shown in Figure 2. A distinctive feature of it is that it peaks at $T \sim 70$ d, a fact that is interesting in view of the long duration of the events recently obtained by the MACHO collaboration (Alcock *et al.* 1996). However, one has also to recall that for their accumulated statistics of $\sim 1.8 \times 10^7$ stars yr, and adopting an average efficiency in this range of event durations $\epsilon \sim 0.3$, one would expect a number of events $N_{ev} \simeq 0.3N_{10}$ arising from the NS.

We have also explored the sensitivity of the results to variations in the assumptions made. Considering a flattened halo changes little the previous predictions. This is because the effects of flattening only affect sizeably the distribution of NS along the line of sight for $|z| > 10$ kpc, and the contribution to the optical depth of lenses in this region is not dominant in any case.

Variations in the radial distribution of initial positions can have some effects on the predictions. For instance, adopting a Gaussian distribution centered at 5 kpc with an extension of 2 kpc, as done by Hartmann *et al.* (1990), increases the optical depth by $\sim 20\%$. Considering NS produced in the inner region of the Galaxy, as e.g. resulting from SN explosions of stars in the Galactic bulge, leads to a smaller optical depth 'per star borned'[2], with events having somewhat larger durations.

There is little sensitivity of the predictions to the details of the assumed velocity distribution, and for instance halving all the initial velocities leaves almost unchanged both τ and $\langle T \rangle$. Most of the contribution to τ comes from NS with intermediate velocities 100 km/s $\lesssim v \lesssim 500$ km/s. For example, if all stars were given initial kicks of 50, 100, 300 or 600 km/s, we would obtain an optical depth $\tau = 0.5, 1.6, 3.0, 0.5 \times 10^{-8} N_{10}$ respectively.

Finally, we would like to note that another logical possibility is that a fraction of the SN explosions leads to black hole (BH) formation rather than to NS. For instance, Timmes *et al.* (1996) have estimated that if all stars more massive than $19 M_\odot$ gave rise to BH rather than to NS, $\sim 70\%$ of the remnants would be BH ($N_{BH} \simeq 1.4 \times 10^9$ according to their estimates). Two important differences would result in this case. The kick velocities imparted to the BH in the explosions, if any, would certainly be smaller, leading to a BH distribution less extended than the one obtained for the NS, and this would tend to reduce the optical depth toward the LMC. Second, the larger average masses of the produced BH would tend to enhance the optical depth proportionally ($\tau \propto \rho \propto \langle m_{BH} \rangle$). If a significant fraction of the BH acquire velocities larger than ~ 100 km/s, the first effect will not be large, as previously discussed, so that the second one would dominate, allowing for an increased value of τ. The larger masses would also imply longer event durations ($T \propto \sqrt{m}$).

In conclusion, we have considered the contribution that NS may provide to the microlensing of LMC stars. Leaving aside the possibility of a pregalactic (population III) NS component (Eichler and Silk 1992, Brainerd 1992), the largest NS population would be the one arising from SN explosions in the Galactic disk, since this is the most massive stellar Galactic component. The resulting optical depth for this population is $\tau \sim 2 \times 10^{-8} N_{10}$, and the event durations are peaked at $T \sim 70$ d. This range of durations is interesting in

[2]For instance, $\tau \simeq 0.8 \times 10^{-8} N_{10}$ for NS born in the inner 1 kpc of the Galaxy.

view of the long event durations observed by the MACHO collaboration, with the longest two having $T = 65$ and 50 d[3] (a larger one, with $T = 71$ d and produced by a binary lens[4], most probably corresponds to a lens in the LMC, due to its measured proper motion, while the events of shorter durations may (at least partially) be ascribed to a faint component of some of the Galactic or LMC stellar populations (see de Rújula *et al.* 1995)). However, for the reference value $N_{10} \simeq 0.2$, the expected event rate from the NS falls below the observed one by an order of magnitude (although the statistics is certainly not large). Only for a larger NS density, $N_{10} \gtrsim 1$, the rates from NS would be significant for the present microlensing searches. Whether such large values are acceptable and consistent with the Galactic chemical evolution remains to be seen. At any rate, the existence of this lensing population certainly made it deserve a quantitative study.

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[3]The determination of the duration is sensitive to the treatment of the blending effects, and for these two events the unblended fit gives $T = 57$ and 43 d respectively. Also note that there is no neat distinction between short and long duration events.

[4]Due to the fact that the large majority of NS are single, a characteristic of the NS events will be the lack of binarity signals

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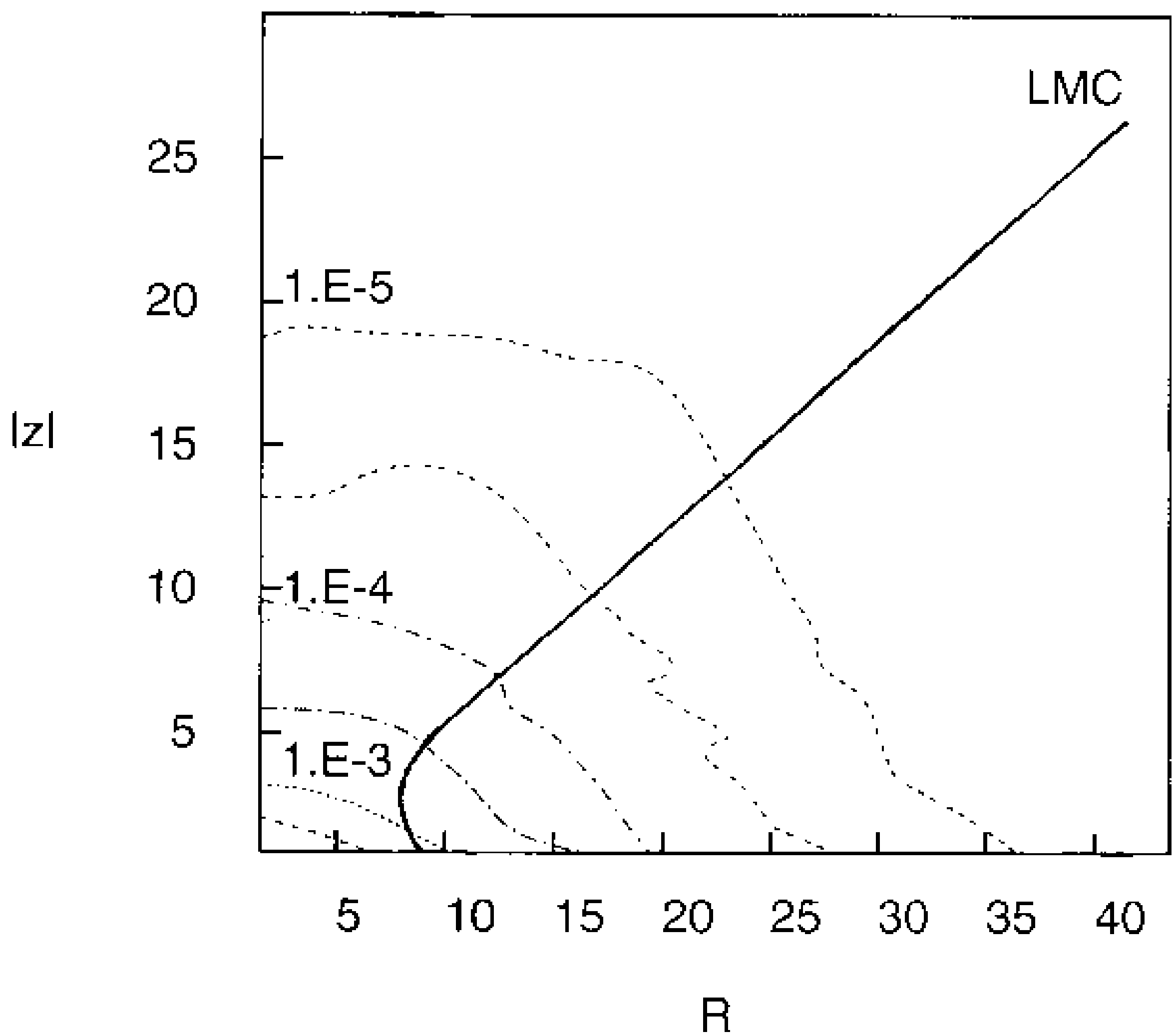
Fig. 1.— Present neutron star density contours vs. cylindrical galactic coordinates. The different contours correspond to N/N_{10} =3.E-3, 1.E-3, 3.E-4, 1.E-4, 3.E-5, 1.E-5 (stars/pc^3). The location of the LMC is indicated as well as the coordinates (solid line) of the line of sight to that galaxy.

Fig. 2.— Differential event rate distribution vs. event duration, taking as normalization $N_{10} = 1$.


LMC
1.E-5
1.E-4
1.E-3
|z|
25
20
15
10
5
5
10
15
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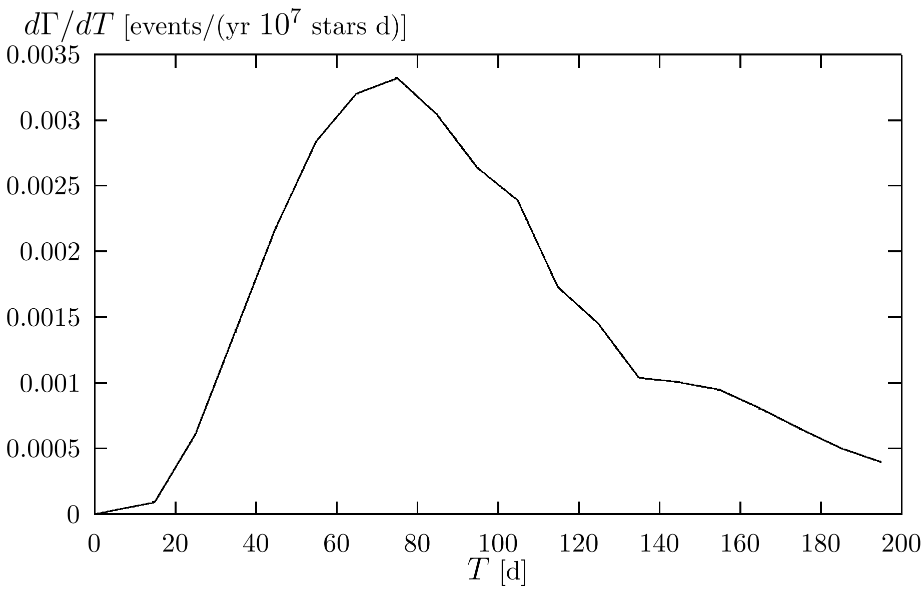
30
35
40
R



$d\Gamma/dT$ [events/(yr 10^7 stars d)]
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
0
20
40
60
80
100
120
140
160
180
200
T [d]